Exergy Analysis and Exergoeconomic Analysis of An Ethylene Process

Hsuan Chang

Department of Chemical Engineering,Tamkang University
Tamsui, Taipei, Taiwan, 251, R.O.C.
E-mail: nhchang@mail.tku.edu.tw

Abstract

This paper presents the results of exergy analysis and exergoeconomic analysis for an ethylene process and its auxiliary refrigeration system. The exergy analysis results indicate that the exergetic efficiencies of the demethanization and the debutanization sections are the lowest. On the other hand, the exergoeconomic analysis results indicate that the increase of the unit thermoeconomic cost of the compression section and the demethanization section are the highest. This study demonstrates that exergoeconomic analysis can provide extra information than exergy analysis and the results from exergoeconomic analysis provide cost-based information suggesting potential locations for process improvement.

Key Words: exergoeconomic analysis, thermoeconomic analysis, ethylene process, energy efficiency

1. Introduction

Ethylene process, which performs the separation and recovery operations for the gaseous product mixtures from the pyrolysis of naphtha or ethane, produces various high-purity petrochemical raw materials, such as ethylene, propylene, etc. Fuge & Sohns [1] and Kaiser et al. [2] have applied exergy analyses on ethylene processes. The analysis allows the evaluation of the exergy losses and exergetical (or second law) efficiencies to identify potential locations for process improvements.

Exergoeconomic analysis is a method combines exergy analysis with economic analysis. The method provides a technique to evaluate the costs of inefficiencies or the costs of individual process streams, including intermediate and final products. The development of exergoeconomic analysis has been reviewed by El-Sayed and Gaggioli [3] and Tsatsaronis [4]. Valero et al. [5] have developed the exergetic cost theory and systematic methodology for evaluation of costs associated with process stream exergy. The application of exergoeconomic methods have been mostly reported for the analysis of energy conversion systems, such as power plants and cogeneration systems [6-10]. There are only very few reports of applications on chemical processes [11, 12]. This paper presents the results of the exergy analysis and the exergoeconomic analysis using the systematic method developed by Valero et al. [5] for a typical ethylene process.

2. Process Design and Simulation

The process analyzed in this study is a design problem developed by Lincoff [13]. The process feed is a pyrolyzed product of a flow rate of 1,365 kton/yr. The composition of the feed stream is listed in Table 1. The major product specifications for the recovery and separation process are summarized in Table 2.

The flow sheet is shown in Figure 1. This process represents a typical naphtha-pyrolysis product recovery and separation process. The process includes a compression section to liquefy the feed stream for distillation separation, a drying/precooling section to remove water and further decrease the temperature, and a distillation train to accomplish the sharp separation of individual components, such as methane, ethylene, propylene, etc. Decisions for major design variables are listed in Table 3. This process is simulated using process simulation software – CHEMCAD^{TM} [14], for material and energy balances, as well as the major equipment costing. The simulation results provide the necessary information of process streams and unit operations for exergoeconomic analysis.

Because the main process involves high-pressure liquefaction of low boiling point components, such as methane, ethane, etc., several very low temperature levels of refrigeration are required for process stream cooling. A refrigeration process involving methane, ethylene and propylene as refrigerants is designed in this study. The flow sheet is shown in Figure 2, and the major design decisions are listed in Table 4. This refrigeration process includes possible energy integration with the main process. This refrigeration process is also simulated by CHEMCAD^{TM} [14].

Table 1. Feed stream conditions of ethylene process
Condition: vapor at 136 kPa, 333K

Component	Flowrate (kton/yr)	Component	Flowrate (kton/yr)
Hydrogen	26.8	Methane	221.6
Ethylene	450.0	Ethane	107.4
Propylene	169.8	Propane	9.8
1,3-Butadiene	64.6	Butylenes	55.4
Steam-Cracked Naphtha	260.1	Water	175.3

Table 2. Product specifications for ethylene process

Component	Specification
H_2	90 mole%, 75% recovery
CH_4	90% recovery
C_2H_4	99.975 mole%, 95% recovery
C_3H_6	92 wt%, 95% recovery
C_4's	95% recovery

Table 3. Major design decisions for ethylene process

Process Unit	Decisions
Compression Section	5 stages with equal compression ratio of 1.91; Adiabatic compression with efficiency of 0.72
Condensate Splitter	Reflux Ratio: 0.4639, No. of Trays: 12
Dryer	Molecular Sieve Dehydration
Demethanizer	Reflux Ratio: 2.552, No. of Trays: 26
H_2/CH_4 Separator	Membrane Separation
Deethanizer	Reflux Ratio: 0.7654, No. of Trays: 39, No. of Columns: 2 Parallel
C-2 Splitter	Reflux Ratio: 3.3, No. of Trays: 85, No. of Columns: 3 Parallel
Depropanizer	Reflux Ratio: 1.8, No. of Trays: 75
Debutanizer	Reflux Ratio: 1.5, No. of Trays: 40

Table 4. Major design decisions for refrigeration system

Process Unit	Decisions
Methane Cycle	1 stage compression (178→450.8psia)
Ethylene Cycle	2-stage compression (17.8→58.6 psia, 58.6→192.4 psia)
Propylene Cycle	3-stage compression (12.4→36 psia, 36→103 psia, 103→330 psia)

3. Exergy Analysis

Exergy analysis combines the first and second laws of thermodynamics, and is a powerful tool for analyzing both the quantity and the quality of energy utilization. Exergy is defined as the maximum work obtainable while the system communicates with environment reversibly [15]. A definition for the most stable environment, so called dead state, is therefore essential to the exergy analysis. In this paper, the dead state definition follows Lozano and Valero [16].

Two definitions of exergy commonly used are physical exergy and chemical exergy. Physical exergy (ex_{ph}) is the maximum work for reaching thermal and mechanical equilibrium with the dead state, while chemical exergy (ex) is the maximum work for reaching also the chemical equilibrium with the dead state.

$$ex_{ph} = (h - h_o) - T_o(s - s_o) \tag{1}$$

$$ex = (h - T_o s) - \sum_{1}^{n_c} x_i \mu_{i,oo} \tag{2}$$

For a steady state open system, the exergy balance equation allows the evaluation of exergy loss (*exl*).

$$\sum_{1}^{n_{in}} m_j ex_j - \sum_{1}^{n_{out}} m_j ex_j + \sum_{1}^{n_Q} Q_j (1-\frac{T_o}{T}) - \sum_{1}^{n_W} W_j - exl = 0$$

The common definitions of exergetic efficiency of a system include:

$$\eta_I = \frac{all\ \ output\ \ \ exergies}{all\ \ input\ \ \ exergies}$$

$$= 1 - \frac{exl}{all\ input\ exergies} \qquad (4)$$

$$\eta_{II} = \frac{all\ \ purpose\ \ \ exergy\ \ \ changes}{all\ \ driving\ \ \ \ force\ \ exergy\ \ \ changes}$$

$$= 1 - \frac{exl}{all\ driving\ \ force\ exergy\ changes} \ (5)$$

The exergy analysis for the ethylene process and the refrigeration system has been conducted at three aggregated levels, namely, (1) the unit operation level, (2) the subsystem level, such as compression section, demethanization section, etc., and (3) the overall process (or system) level. The results (η_{II}) of the level (2) and level (3) for the ethylene process and the refrigeration system are summarized in Figures 3 and 4. For the ethylene process, the efficiencies of subsystem level various from 7% to 57%, with the demethanization section and the debutanization section show lowest efficiencies at 15% and 7%, respectively. The efficiencies of the distillation separation sections are all very low, ranges from 7% to 28%. The overall process efficiency is 35%. As for the refrigeration system, the three individual cycles show close efficiencies of about 80%.

4. Exergoeconomic Analysis

Valero's method [5] allocates the cost of feed streams, operating cost and capital cost of each unit operation to its product streams. Exergetic cost (*EXC*) is the expense, in terms of exergy, for obtaining a process stream, while the thermoeconomic cost (*TEC*) is the monetary expense for obtaining a process stream.

An incidence matrix, ***A***, consists of three types of information: (1) the input-output stream information for each unit operation; (2) the specifications for the input streams to the overall system, (3) the independent cost relations among streams based on the specifications of purpose and driving forces for each unit operation.(3)The exergetic cost of each individual stream of the system can be determined by solving the following equation:

$$\boldsymbol{AE=Y} \qquad (6)$$

E is the vector of *EXC* of all streams. ***Y*** is a vector consists of the information corresponding to the above mentioned three parts of matrix ***A***, i.e. the exergy balance of each unit operation, the exergy of input streams to the overall system, and the independent cost balances.

The unit exergetic cost, which is the exergetic cost per unit exergy, of stream *j* (exc_j) is defined as:

$$exc_j = \frac{EXC_j}{ex_j} \qquad (7)$$

When the monetary costs are considered for analysis, the thermoeconomic cost of each individual stream can be determined. The costs include overall system's input stream costs, which also include the utility stream costs, equipment costs, and operating and maintenance costs. Similar to the exergetic costs, the thermoeconomic costs can be determined by solving the following equation:

$$\boldsymbol{AT=Z} \qquad (8)$$

T is the vector of *TEC* of all streams. ***Z*** is a similar vector to ***Y***, however the information consists of the monetary balance of each unit operation (requires equipment costs), the monetary costs of input streams to the overall system, and the independent cost balances.

The unit thermoeconomic cost, which is the thermoeconomic cost per unit exergy, of stream *j* (tec_j) is defined as:

$$tec_j = \frac{TEC_j}{ex_j} \qquad (9)$$

The results of exergoeconomic analysis of the ethylene process are summarized in Figure 5 and Figure 6. The former considers only energy costs of utility streams to the overall process and the cost of pyrolyzed feed stream is assigned to be zero. To account for the costs of refrigerants used in the ethylene process, the unit thermoeconomic costs of various levels of refrigerants determined from the analysis of refrigeration systems are used while conducting the analysis of ethylene process. When equipment costs are included in the analysis, the capital costs of equipments are equally amortized in three years. The results shown in both figures indicate that compression section and demethanization section are the two subsystems with the most significant increase of unit thermoeconomic costs between their input and output streams. For these two sections, the unit thermoeconomic costs increase from 0 to 566 USD/10^9 kcal and 750 to 2121 USD/10^9 kcal if only energy costs are considered in the analysis. When equipment costs are considered too, the unit thermoeconomic costs increase from 0 to 972 USD/10^9 kcal and 1170 to 2977 USD/10^9 kcal. The information suggests that these two sections are most potent for significant improvements. On the other hand, the exergetic efficiencies of these two sections, i.e. 57% and 15% respectively, indicate the room to the theoretical limit for improvements.

For refrigeration system, unit thermoeconomic costs of various levels of utility supplied are summarized in Table 5. The analysis assigns different costs for different levels of cooling or heating utilities, ranging from 91.4~148.7 USD/10^6 kcal. Due to the complexity of energy integration within the cascaded three refrigeration cycles, the costs of utilities do not show uniform increase for decrease of cooling level or increase of heating level.

Table 5. Unit Thermoeconomic Costs of Utilities Supplied by Refrigeration System

Type of Utility	Level of Utility(K)	Cost (USD/10^6 kcal)
Cooling	153	148.7
	227	85.9
	253	92.4
	285	120.2
Heating	248	101
	274	91.4

5. Conclusions

This paper presents the methods and results of applying both exergy analysis and exergoeconomic analysis on a typical large scale petrochemical process, i.e. an ethylene process with its auxiliary refrigeration system. Before conducting the exergy or exergoeconomic analysis, a rigorous process simulation is accomplished by a process simulation software, CHEMCAD™.

The exergy analysis results indicate that the demethanization section and the debutanization section are most inefficient in terms of exergetic efficiency, in particularly, the efficiency of the debutanization section is the lowest of only 7%.

However, the results of exergoconomic analysis indicate that the compression section and the demethanization section have highest potential for energy improvement in terms of the unit thermoeconomic cost increase of input and output streams. This conclusion holds under both conditions, i.e. considering only energy costs or considering both energy and equipment costs.

Therefore, one can conclude from this study that exergoeconomic analysis can provide extra information than exergy analysis. The results from exergoeconomic analysis suggest cost-based information for identifying potential locations for process improvement.

Nomenclature

$\boldsymbol{A}$	incidence matrix
$\boldsymbol{E}$	vector of exergetic cost
ex	exergy
exc	unit exergetic cost
EXC	exergetic cost
exl	exergy loss
h	enthalpy
m	flowrate
Q	heat transfer rate
s	entropy
$\boldsymbol{T}$	vector of thermoeconomic cost
T	temperature
tec	unit thermoeconomic cost
TEC	thermoeconomic cost
W	work transfer rate
x	composition
$\boldsymbol{Y}$	vector associated with $\boldsymbol{A}$ and $\boldsymbol{E}$
$\boldsymbol{Z}$	vector associated with $\boldsymbol{A}$ and $\boldsymbol{T}$
Greeks	
η	efficiency
μ	chemical potential
Subscripts	
i	component *i*
j	stream *j*
n_c	number of component
n_{in}	number of input streams
n_{out}	number of output streams

n_Q	number of heat transfers
n_W	number of work transfers
o	dead state
oo	dead state for component

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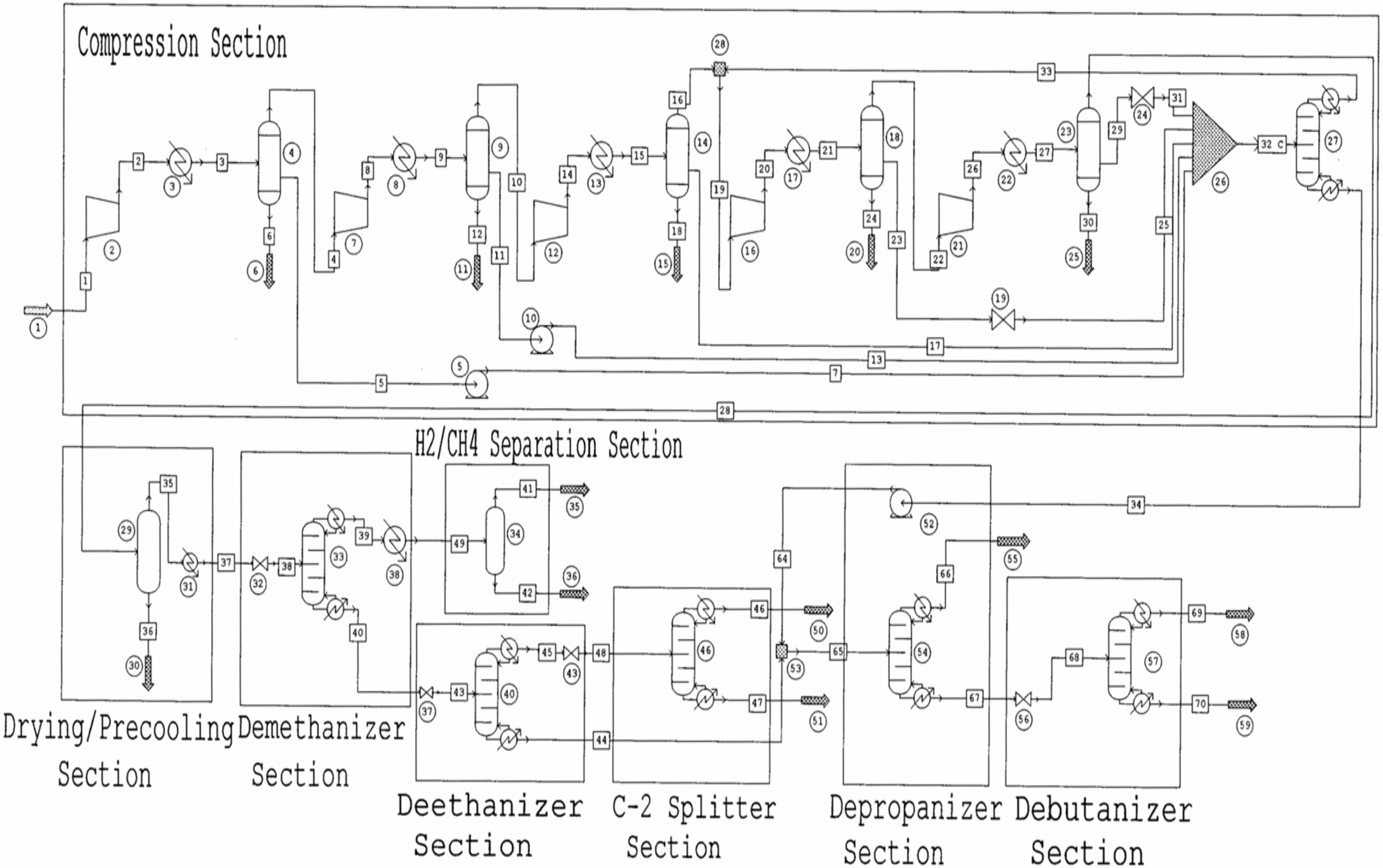

Figure 1. Ethylene process flow diagram

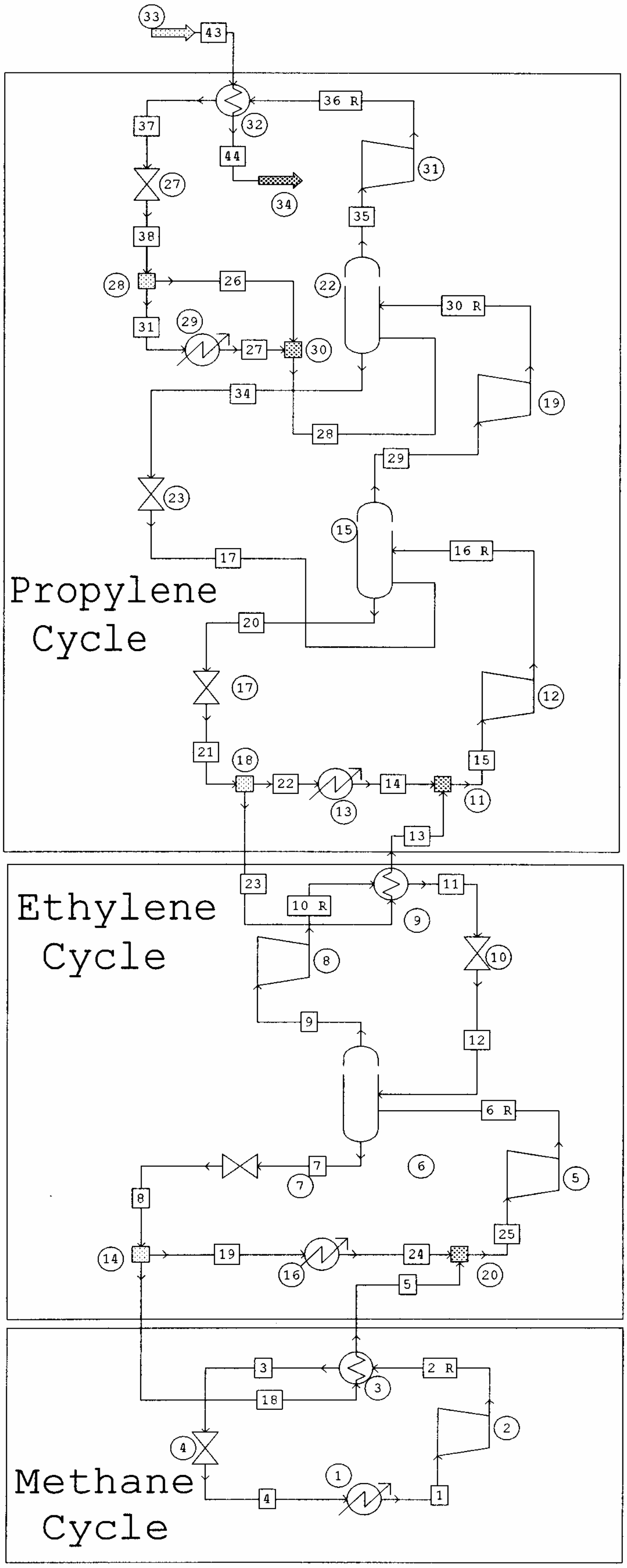

Figure 2. Refrigeration system flow diagram

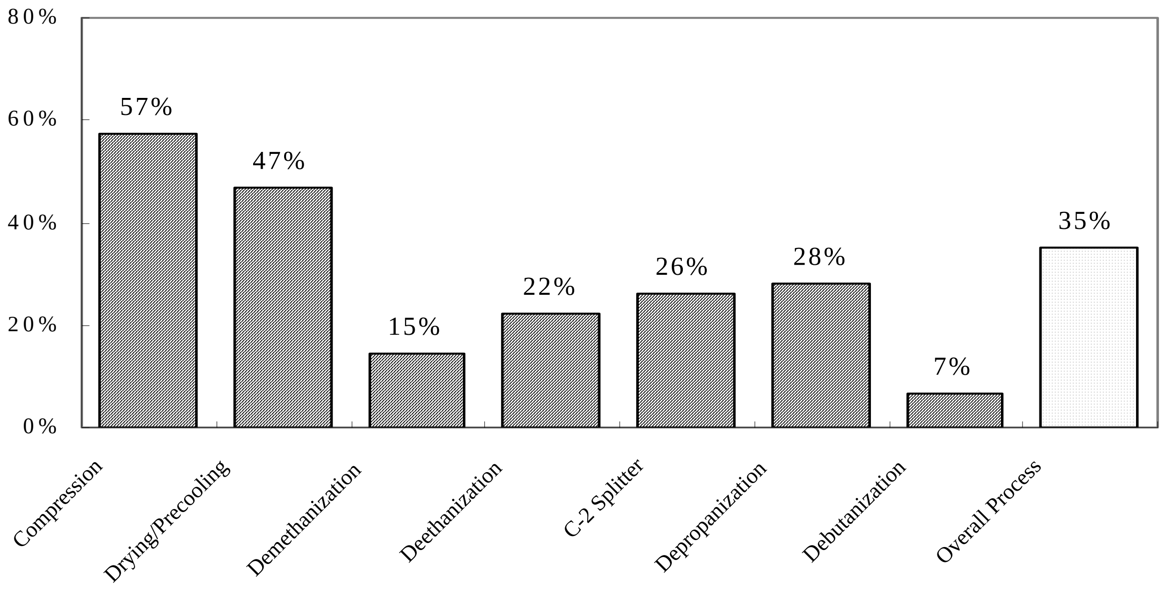

Figure 3. Exergetic efficiencies of the subsystem level and the overall process level for the ethylene process

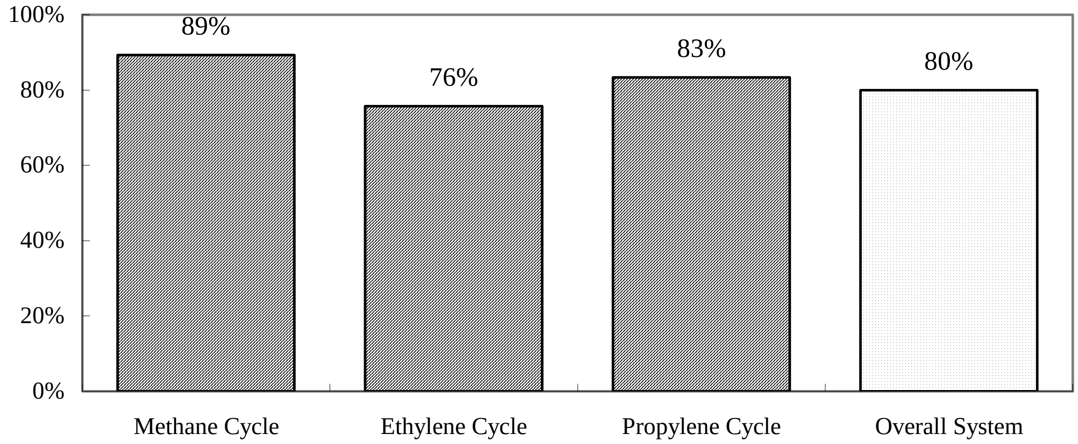

Figure 4. Exergetic efficiencies of the subsystem level and the overall process level for the refrigeration system

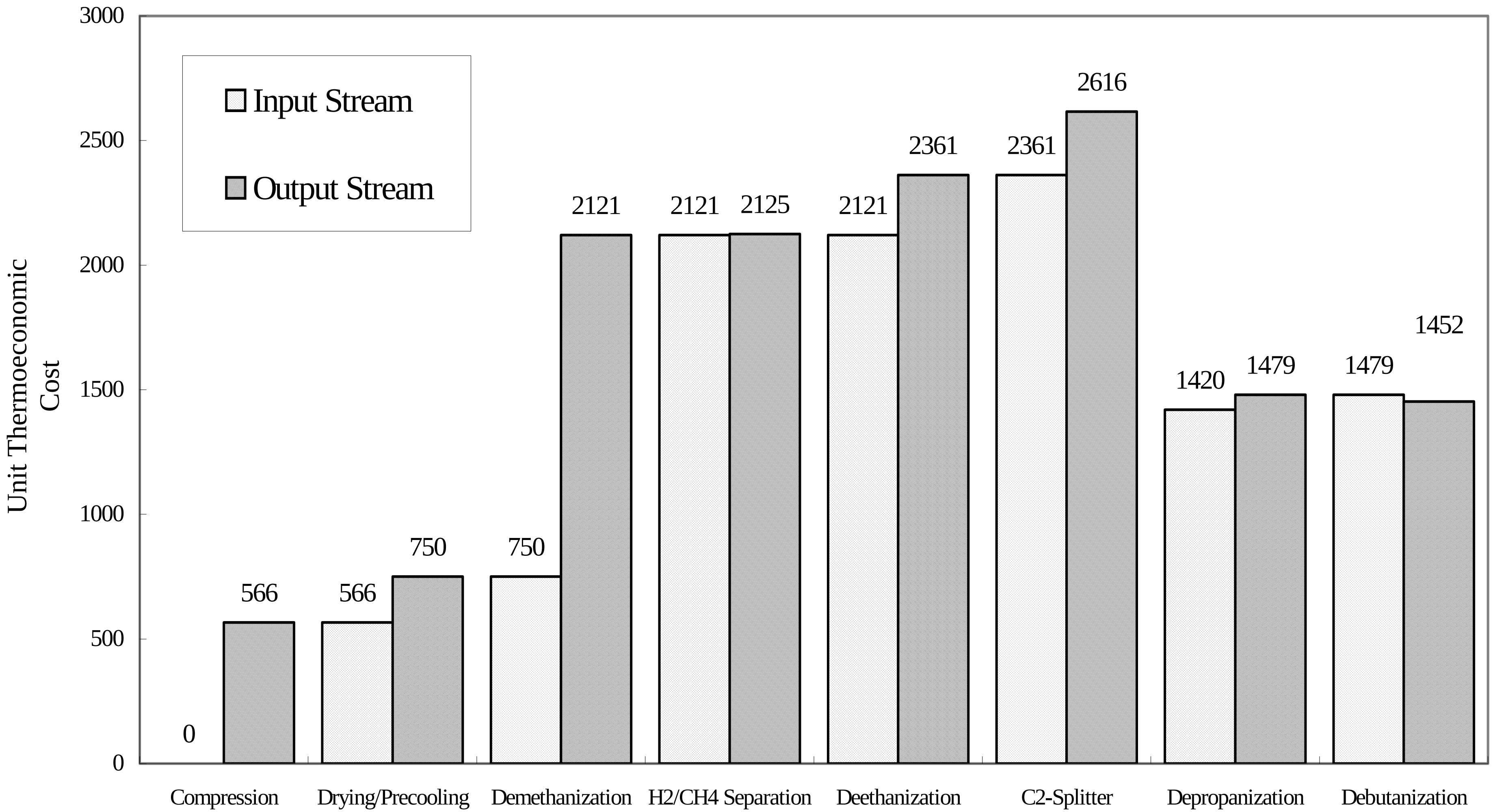

Figure 5. Unit thermoeconomic costs (USD/10^9 kcal) of ethylene process – consider energy costs only

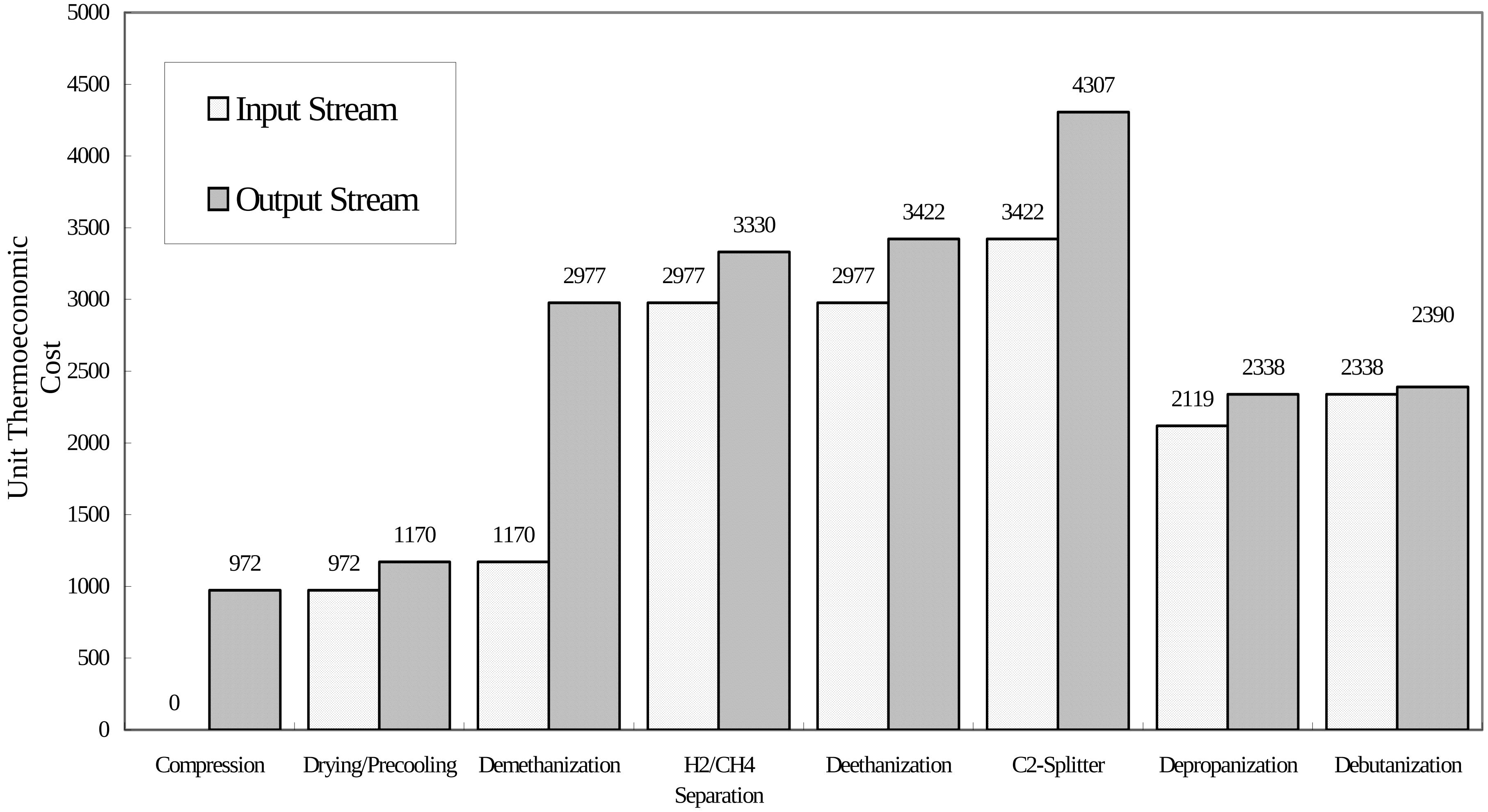

Figure 6. Unit thermoeconomic costs (USD/10^9 kcal) of ethylene process – consider both energy and equipment costs